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Supernovae Types Ia/II and Intracluster Medium Enrichment

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ABSTRACT
We re-examine the respective roles played by supernovae (SNe) Types Ia and II in enriching the intracluster medium (ICM) of galaxy clusters, in light of the recent downward shift of the ASCA abundance ratios of α-elements to iron favoured by Ishimaru & Arimoto (1997, PASJ, 49, 1). Because of this shift, Ishimaru & Arimoto conclude that $\gtrsim 50\%$ of the ICM iron must have originated from within Type Ia SNe progenitors. A point not appreciated in their study, nor in most previous analyses, is the crucial dependence of such a conclusion upon the adopted massive star physics. Employing several alternative Type II SN yield compilations, we demonstrate how uncertainties in the treatment of convection and mass-loss can radically alter our perception of the relative importance of Type Ia and II SNe as ICM polluters. If mass-loss of the form favoured by Maeder (1992, A&A, 264, 105) or convection of the form favoured by Arnett (1996, Supernovae and Nucleosynthesis) is assumed, the effect upon the oxygen yields would lead us to conclude that Type Ia SNe play no part in polluting the ICM, in contradiction with Ishimaru & Arimoto. Apparent dichotomies still exist (e.g., the mean ICM neon-to-iron ratio implies a $\sim 100\%$ Type II Fe origin, while the mean sulphur ratio indicates a $\sim 100\%$ Type Ia origin) that cannot be reconciled with the currently available yield tables.

Key words: galaxies: elliptical — galaxies: evolution — galaxies: intergalactic medium – galaxies: X-rays — supernovae

1 INTRODUCTION

Evidence for supersolar abundance ratios of α-elements to iron (i.e. [α/Fe]$\gtrsim$ +0.0) in the intracluster medium (ICM) of the Virgo, Perseus, and Abell 576 galaxy clusters has been available in the literature since the mid-1980s (Canizares et al. 1982, Canizares, Markert & Donahue 1988, and Rothenflug et al. 1984), although these measurements were heavily weighted towards thermally-complex cooling flow regions. Much debate in the subsequent years has centred on the robustness of these results, in light of the difficulty in obtaining accurate abundances for the α-elements. Taking advantage of the unique characteristics of the *Advanced Satellite for Cosmology and Astrophysics* (ASCA), Mushotzky et al. (1996) determined the ICM abundance ratios for four clusters and found, using the solar photospheric abundance scale, the following unweighted mean (SIS) values: [O/Fe]≈+0.18, [Si/Fe]≈+0.31, [Ne/Fe]≈+0.29, [S/Fe]≈-0.11, and [Mg/Fe]≈+0.07. Scaling to the meteoritic abundances, Ishimaru & Arimoto (1997) revised these values to: [O/Fe]≈+0.01, [Si/Fe]≈+0.14, [Ne/Fe]≈+0.12, [S/Fe]≈-0.32, and [Mg/Fe]≈-0.10. Similar results are becoming available for ~ 10 additional clusters. Both "scalings" were based upon Table 1 of Anders & Grevesse (1989).

The abundance ratio pattern in the ICM provides a unique tool with which to probe the origin of these heavy elements. While the favoured mechanism for enriching the ICM is supernovae (SNe)-driven winds from elliptical galaxies (e.g., Gibson 1997, and references therein), there is still no consensus as to whether these winds are dominated by the ejecta of Type II SNe (either via initial mass functions heavily-weighted towards their progenitors or via an early wind relatively unpolluted by the longer-lived progenitors to Type Ia SNe) or Type Ia SNe. Since *a priori* galactic wind models can be constructed to satisfy either scenario (e.g., Matteucci & Vettolani 1988; Gibson & Matteucci 1997), it was recognised that accurate cluster ICM abundance determinations might allow discrimination between these two competing scenarios (simply by comparing with the abundance ratio pattern for any Type II or Type Ia SNe predominance).

Recently Ishimaru & Arimoto (1997), utilizing the meteoritic abundance scaling and Type II SN yields from Tsujimoto et al. (1995), concluded that $\gtrsim 50\%$ of the ICM Fe

originated from Type Ia SNe. Loewenstein & Mushotzky (1996), using self-consistent arguments independent of the assumed solar abundance scaling (despite implications to the contrary in Ishimaru & Arimoto 1997), showed that models where all of the enrichment was due to Type II SN were consistent with the ASCA data – although they took care to note that a significant Type Ia SNe contribution to the Fe enrichment could not be ruled out. The important difference in their models was the adoption of Type II SN yields from Woosley & Weaver (1995). It is our goal herein to more fully and systematically examine how these Type Ia versus Type II ICM iron contribution arguments are *crucially* dependent upon the adopted theoretical Type II SNe yields. Such an appreciation was not apparent in Ishimaru & Arimoto (1997), who erroneously attributed their relatively high inferred Type Ia SNe contribution to the ICM Fe enrichment to their rescaling of the original Mushotzky et al. (1996) abundance ratio determinations; in fact their conclusions were tied inexorably to the Tsujimoto et al. (1995) yields.

In Section 2, we present the basic framework necessary to replicate the Ishimaru & Arimoto (1997) analysis. Instead of restricting ourselves to a single Type II SNe yield compilation, though, we consider several competitors. We list their inherent differences (e.g., differing treatments of convection, mass-loss, reaction rates) and concentrate on their effects upon the predicted ICM elemental abundance ratios. In what follows, we are solely interested in abundance *ratio* questions, and thus for simplicity's sake we shall simply adopt the Salpeter (1955) IMF used by Ishimaru & Arimoto. Arguments pertaining to *absolute* abundance masses favour an IMF biased toward massive stars (e.g., Loewenstein & Mushotzky 1996; Gibson & Matteucci 1997), but these are not particularly relevant to the analysis that follows.

Will we have a definitive answer to the question of Type Ia versus Type II ICM iron origin at the conclusion of this paper? To anticipate our conclusions, no. What we hope to leave with the reader is a better appreciation of the uncertainties involved, and in particular, how a definitive answer *cannot* be reached until further convergence of Type II SNe models is achieved. Our results are summarised in Section 3.

2 ANALYSIS

In order to quantify the roles played by SNe Types Ia and II in contributing to the ICM heavy element abundances, we make use of the formalism presented in Ishimaru & Arimoto (1997). Let us restrict ourselves, for the time being, to the question of the ICM iron origins. We write the fractional contribution of SNe Type Ia to the ICM iron as

$$\frac{\mathrm{M}_{\mathrm{Fe,SNIa}}}{\mathrm{M}_{\mathrm{Fe,total}}} = \frac{\zeta y_{\mathrm{Fe,SNIa}}}{\zeta y_{\mathrm{Fe,SNIa}} + (1-\zeta) < y_{\mathrm{Fe,SNII}} >}, \tag{1}$$

where ζ is the frequency of Type Ia relative to Type II SNe. The iron yield averaged over the Type II SN progenitor IMF, $\phi \propto m^{-x}$, is written

$$< y_{\mathrm{Fe,SNII}} > = \frac{\int_{m_\ell}^{m_u} y_{\mathrm{Fe,SNII}}(m)\phi(m)m^{-1}\mathrm{d}m}{\int_{m_\ell}^{m_u} \phi(m)m^{-1}\mathrm{d}m}. \tag{2}$$

The bounds for Type II SNe progenitors are taken to be $m_\ell = 10$ M$_\odot$ and $m_u = 50$ M$_\odot$, respectively, and an IMF slope $x = 1.35$ (Salpeter 1955) is adopted throughout. We have purposefully avoided considering x as an additional free parameter in the analysis. While this slope is of prime importance for arguments concerning the absolute mass of elements in the ICM (e.g., Loewenstein & Mushotzky 1996), it is less so for abundance *ratios*.

The primary ingredients in the analysis that follows are the adopted nucleosynthesis sources. For Type Ia SNe, the yield appears to be independent of progenitor model, and hence we adopt the updated Model W7 yields of Thielemann, Nomoto & Hashimoto (1993) – the lower portion of Table 1 lists the Type Ia yields $< y_{i,\mathrm{SNIa}} >$.

For Type II SNe, the situation is not so clear; there are large differences in the predicted yields as a function of mass sequence mass and metallicity – the treatment of convection and mass-loss, in particular, are highly uncertain. For what follows, we have chosen a representative sample of the Type II SNe yields on offer in the literature – (i) Tsujimoto et al. (1995) ['T95' in Tables 1 and 2], which formed the basis of Ishimaru & Arimoto's (1997) analysis. These models adopt the Schwarzschild criterion for convection, and are not evolved self-consistently from the zero age main sequence (i.e. the models are pure helium stars, with some assumed He core mass–main sequence mass relation). The $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate is that of Caughlan et al. (1985). Stellar winds have not been considered in these models. (ii) Woosley & Weaver's (1995) Z=Z$_\odot$ and Z=10^{-4}Z$_\odot$ yields, for both Case A and B SN piston energetics ['W95;A;Z$_\odot$' and 'W95;B;Z$_\odot$', 'W95;A;10^{-4}Z$_\odot$' and 'W95;B;10^{-4}Z$_\odot$'] have been included in our analysis. In their Case B, the final kinetic ejecta energy was boosted from $\sim 1.2\times10^{51}$ erg to $\sim 1.9\times10^{51}$ erg in order to reduce the effects of reimplosion of explosively synthesized material. Unlike the Tsujimoto et al. (1995) models, this grid has been evolved self-consistently from the ZAMS, using a $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate that is $\sim$ 74% that of the Caughlan et al. (1985) rate used by Tsujimoto et al. and Thielemann et al. (1996). Woosley & Weaver use the Ledoux convection criterion, with modifications for semiconvection. Again, no pre-SN mass-loss is considered in their models. Woosley & Weaver (1996) only provide the *total* mass of a particular element ejected from a star of mass m and metallicity Z – including both the newly synthesised material as well as the initially present, unprocessed, ejecta. (iii) Maeder's (1992) oxygen yields are considered in tandem with the iron yields of Tsujimoto et al. (1995) ['T95+M92']. Maeder, along with Langer & Henkel (1995), represent the only published grid of yields incorporating mass-loss. Maeder uses the Schwarzschild criterion for convection, like Tsujimoto et al. , but also includes some degree of overshooting. Oxygen production is severely hampered in $m \gtrsim 30$ M$_\odot$ models with solar metallicity,⋆ a result that has profound implications for the Type Ia versus Type II ICM iron argument of Ishimaru & Arimoto (1997).

⋆ The $m \gtrsim 30$ M$_\odot$, Z=Z$_\odot$, models in the Maeder 1992 grid lose their hydrogen-rich envelopes and evolve into Wolf-Rayet stars. Substantial mass-loss continues through core helium burning, greatly enhancing the helium and (during later phases) the carbon yields, at the expense of reduced "fuel" availability for processing beyond oxygen.

Table 1. Average stellar yield in solar masses for the SNe grids under consideration here – T95=Tsujimoto et al. 1995, M92=Maeder 1992, W95=Woosley & Weaver 1995, A96=Arnett 1996, LH95=Langer & Henkel 1995, TNH=Thielemann et al. 1993. Top block - Type II SNe: averaged over the progenitor mass range 10 → 50 $M_\odot$, for a Salpeter (1955) IMF. Linear extrapolation in mass, from the two lowest mass models in the respective grids to $m = 10$ $M_\odot$, assumed. Bottom block - Type Ia SNe: mass independent.

Yield Source	$< y_{\rm Fe,SNII} >$	$< y_{\rm O,SNII} >$	$< y_{\rm Si,SNII} >$	$< y_{\rm Mg,SNII} >$	$< y_{\rm Ne,SNII} >$	$< y_{\rm S,SNII} >$
A96	0.071	0.593	n/a	0.054	0.101	n/a
T95	0.121	1.777	0.133	0.118	0.232	0.040
T95+M92	0.121	0.923	n/a	n/a	n/a	n/a
W95;A;$10^{-4}$$Z_\odot$	0.073	0.806	0.104	0.036	0.095	0.059
W95;B;$10^{-4}$$Z_\odot$	0.085	1.455	0.118	0.066	0.223	0.065
W95;A;$Z_\odot$	0.113	1.217	0.124	0.065	0.181	0.058
W95;B;$Z_\odot$	0.141	1.664	0.143	0.094	0.265	0.064
Yield Source	$< y_{\rm Fe,SNIa} >$	$< y_{\rm O,SNIa} >$	$< y_{\rm Si,SNIa} >$	$< y_{\rm Mg,SNIa} >$	$< y_{\rm Ne,SNIa} >$	$< y_{\rm S,SNIa} >$
TNH93	0.744	0.148	0.158	0.009	0.005	0.086

Table 2. Comparison of input physics for the five Type II SNe models discussed herein. Abbreviations as noted in the caption to Table 1. Yes/No entries refer to the inclusion (or not) of pre-SN mass-loss (column 2), unprocessed metals in the ejecta (column 6), and the effects of explosive nucleosynthesis (column 7). The ^{12}C$(\alpha,\gamma)^{16}$O reaction rate is quoted relative to that of Caughlan et al. (1985) (column 4). The SN progenitor metallicity (column 5), intial evolutionary state (i.e. pure helium star (He) or zero age main sequence (ZAMS)) (column 8), and adopted convection treatment (Sch=Schwarzschild, Led=Ledoux, over=overshooting, semi=semiconvection, ad=adiabaticity, chem hom=chemical homogeneity, and semi hom=semiconvection region homogeneity) (column 3) are noted.

Yield Source	$\dot{\rm M}$(?)	Convection	^{12}C$(\alpha,\gamma)^{16}$O	Z	$\rm m^{unp}$(?)	exp nuc(?)	init state
T95	N	Sch	C85	$Z_\odot$	N	Y	He
M92	Y	Sch+over	C85	$Z_\odot/20$	N	N	ZAMS
W95	N	Led+semi	0.74×C85	$Z_\odot/10$	Y	Y	ZAMS
A96	N	ad+chem hom+semi hom	0.74×C85	$Z_\odot$	Y	N	ZAMS
LH95	Y	∼Led+semi	0.74×C85	$Z_\odot/10$	Y	N	ZAMS

A direct mapping of Maeder's oxygen yields onto the Tsujimoto et al. yields, is not optimal by any means, but it does provide a tantalising clue to the importance of mass-loss consideration. (iv) Arnett's (1996) oxygen, magnesium, and neon yields have been coupled to his earlier iron predictions (Arnett 1991) ['A96']. This has been necessary as the 1996 models contain yields arising from hydrostatic evolution only. Explosive nucleosynthesis can modify the silicon, sulphur, and iron results substantially (Bazán 1997, priv comm). Arnett's new grid of SN models avoids the use of mixing-length theory with semiconvection (e.g., Woosley & Weaver 1996), and assumes that convection is so efficient that complete adiabaticity and chemical homogeneity are maintained. Semiconvective regions are also assumed to be homogeneous.

By considering Type II SN yields from progenitors with uniform metallicities, we have implicitly ignored the effects of galaxy evolution. In principle, one ought to couple models of galaxy formation and chemical evolution directly to the SNII explosion calculations to determine self-consistent integrated nucleosynthetic yields. These would be superpositions of enrichment from Type II SNe with progenitors of varying metallicity. By including both high and low WW95 metallcities we do bracket the expected range of average yields for that subset of our models, and provide some indication of the general effects of varying the progenitor abundances.

A full discussion of the input physics differences, and their respective implications, in each of the above SNe models, is well beyond the scope of this paper. The reader is strongly urged to turn to Woosley & Weaver (1995), Arnett (1996), and Langer† (1997), for details. For a specific analysis of the implications for oxygen, the latter reference is particularly recommended. Table 2 is our attempt at listing, in as concise a manner as possible, the relevant differences between the Type II SNe yield sources adopted in our study.

We are now in a position to quantify the effect of different input physics on our analysis, by simply examining the predicted $< y_{i,\rm SNII} >$ (recall equation 2 for each of the yield sources under consideration); the upper portion of Table 1 provides this information for the Salpeter (1955) IMF noted previously. While it should be apparent that for some elements (e.g., Si and S), agreement at the ∼ 50% level exists, differences of factors of ∼ 2 → 3 persist in the important Fe and O yields. These large differences should immediately hint at a potential problem in quantifying the exact ratio of Type Ia to Type II SNe contribution to the ICM heavy elements, a point to which we return shortly.

† Figures 1 and 2 in Langer's (1997) oxygen yield comparison are particularly relevant. His figure 1 demonstrates the factor of two difference that exists between models with the *same* convection treatment, while his figure 2 highlights a further factor of three uncertainty, due to the assumptions regarding semiconvection. On an even more sombre note, Bazán & Arnett's (1997) multi-dimensional hydrodynamical simulations of oxygen shell burning during the pre-core collapse call into question the entire validity of the one-dimensional diffusion-like algorithms that have been previously used (and are inherently assumed in each of the yield compilations adopted in this paper)!

Having determined the mean stellar yields for both Type Ia and II SNe, for the IMF under consideration, we can now use equations 1 and 2 (and their analogs for other elements) to compute the ICM abundance ratios [O,Si,Mg,Ne,S/Fe] as a function of $M_{Fe,SNIa}/M_{Fe,total}$. The results of this can be seen in Figure 1 – the seven different yield source possibilities are labeled, and the horizontal dotted curve in each frame represents the mean of Mushotzky et al. 's (1996) ASCA SIS data, as scaled by Ishimaru & Arimoto (1997). Our models adopt the meteoritic abundance scale of Anders & Grevesse (1989).

The solid curves are a reasonable representation of the Ishimaru & Arimoto (1997) models - an exact match is difficult as their exact handling of the yield extrapolation in the $10 \rightarrow 13$ M$_\odot$ range is not provided. On the surface, this may seem a trivial matter, but one should bear in mind that approximately one fifth of the Type II progenitor mass is tied up in the $10 \rightarrow 13$ M$_\odot$ region of the IMF under consideration. "Blind" linear extrapolation (as adopted here), extrapolation from the $m = 13$ M$_\odot$ yields down to effectively zero, or simply setting all yields for masses below 13 M$_\odot$ to some arbitrary value, all lead to further factors of ~ 2 uncertainties in the results, a point alluded to by Ishimaru & Arimoto.

The important result to take from Figure 1 is the intersection of the various curves with the mean of the ASCA SIS data. Table 3 provides the "intersection" information for each model – i.e. for each element, the fraction of that element originating from Type Ia SNe (the numerators) required to match the mean of the ASCA SIS ICM abundance, and the corresponding fraction of ICM iron from Type Ia SNe (the denominators). Because oxygen, silicon, and iron have the best-determined abundances (Mushotzky et al. 1996), Ishimaru & Arimoto (1997) base the bulk of their conclusions upon the [O/Fe] and [Si/Fe] plots, so let us concentrate on these elements for the time being.

From the solid curves in the top two panels of Figure 1 (or the corresponding entries in Table 3), we can see that Ishimaru & Arimoto (1997) favour a Type Ia iron fractional contribution to the ICM of $\sim 48\%$ and $\sim 38\%$, based upon oxygen and silicon, respectively, because of their use of the Tsujimoto et al. (1995) yields [‡]. Simply replacing the Tsujimoto et al. yields with those of Woosley & Weaver (1995) would allow anything in the range of $\sim 30 \rightarrow 55\%$, depending upon assumed SNe energetics (an important consideration in determining the amount of Si, S, and Fe, for example, that fall back onto the collapsed remnant) and progenitor metallicity.

Of particular interest is the behaviour of the [O/Fe] models when the effects of Maeder (1992)-style mass-loss or Arnett (1996)-style convection are taken into account. Here we are somewhat restricted in that both these grids only consider hydrostatic evolution; the effects of explosive nucleosynthesis upon the yields are not included, and these can be profound for Si, S, and Fe. Thusly, we simply examine O (for the Maeder grid) and O, Mg, and Ne (for the Arnett grid), adopting reasonable assumptions for the Fe for each grid – Tsujimoto et al. 1995, for Maeder (because of some convection-treatment similarities), and Arnett 1991, for Arnett (for obvious reasons).

Perhaps the most important result to take away from our study is the behaviour of these Arnett (1996) and Maeder (1992) models (A96 and T95+M92, respectively) in Figure 1 (and Table 3). For these Type II SNe yield sources, any model that includes an ICM Type Ia iron fractional contribution $\gtrsim 5\%$ is at odds with the mean of the ASCA SIS cluster data.This appears to be a fairly robust conclusion – the most modern treatments of convection and mass-loss *both* act in the direction of favouring a dominant Type II origin to the ICM iron abundance. [§]

Unfortunately, while oxygen may be pointing toward a Type II SNe origin to the ICM abundances, the situation with silicon (the other element that Ishimaru & Arimoto 1997 considered as the most important in their analysis) is not so obvious. An ICM Type Ia iron fractional contribution in the range $\sim 30 \rightarrow 55\%$ is allowed by the current grid of Type II SNe models, but we cannot, as of yet, quantify accurately the effects of mass-loss and other convection treatments (a la Maeder 1992 and Arnett 1996) on the silicon yields, as both these models only considered hydrostatic evolution. Explosive nucleosynthesis computations for these grids are eagerly anticipated.

While Mg, Ne, and S are usually given less weight in these ICM abundance analyses (see Mushotzky et al. 1996 for a discussion of the inherent difficulties in accurately determining their respective abundances), their behaviour in the $[X_i/Fe] - M_{Fe,SNIa}/M_{Fe,total}$ plane (Figure 1) is nonetheless interesting. (i) The Tsujimoto et al. (1995) [Mg/Fe] ratios are significantly higher than those of Woosley & Weaver (1995) and, to a lesser extent, Arnett (1996). While adopting the latter would lead one to conclude that Type Ia SNe contribute $\sim 15 \rightarrow 45\%$ of the ICM Fe, Ishimaru & Arimoto (1997), because they followed Tsujimoto et al. , favour $\sim 60\%$. (ii) There is an apparent dichotomy between the neon and sulphur results. One must be cautious against putting too much weight on the neon observations, due to potential systematic problems (Mushotzky et al. 1996). On the other hand, as already commented upon in Mushotzky et al. (1996) and Loewenstein & Mushotzky (1996), there would appear to be no escape from the fact that the sulphur abundances are at odds with a Type II-dominated origin to the ICM iron abundance (although the uncertainties are large). This appears to be entirely independent of adopted Type II SNe yields.

[‡] We should note though that if the massive star IMF slope is closer to the Scalo (1986) value of $x \approx 1.7$, as opposed to the Salpeter (1955) value of $x \approx 1.35$, then the implied ICM $M_{Fe,SNIa}/M_{Fe,SNII}$ ratios for oxygen and silicon would be reduced from ~ 0.48 and ~ 0.38, respectively, to ~ 0.32 and ~ 0.26, respectively, thereby strengthening the support for a $\sim 3 \rightarrow 4\times$ Type II-to-Type Ia predominance ratio.

[§] We have not shown the behaviour of Langer & Henkel's (1995) oxygen yields, calculated in the presence of pre-SN mass-loss, coupled to the iron yields of Woosley & Weaver (1995), to whom their convection treatment most closely resembles. The former's predictions regarding the mass of ejected oxygen parallels almost exactly that of Arnett (1996), and their mapping onto the models of Woosley & Weaver (1995) would likewise tend to indicate a dominant role for Type II SNe in ICM enrichment – analogous to the case of the M92 extension of the Tsujimoto et al. (1995) models.

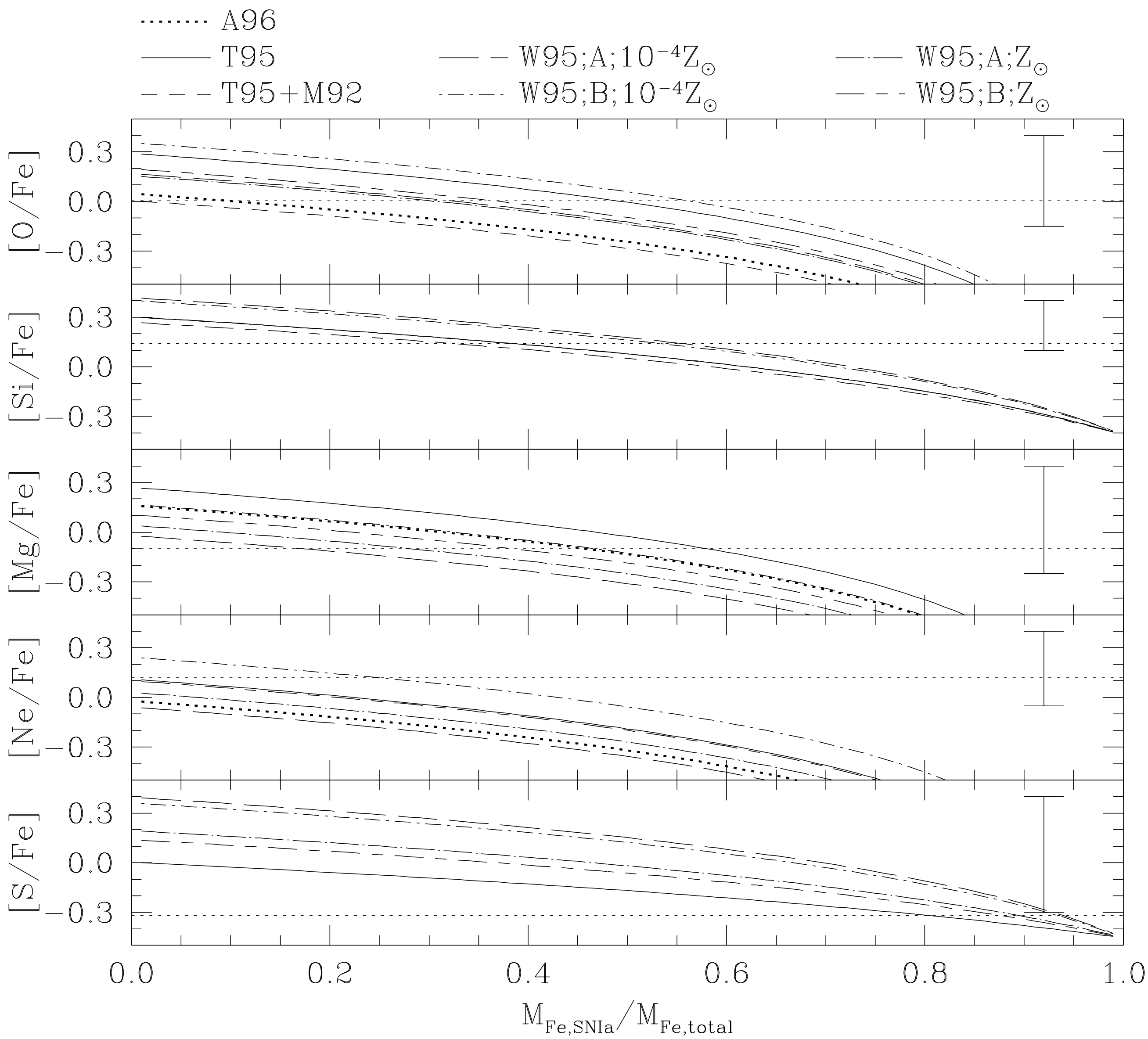

Figure 1. Ratio of relative abundance [X_i/Fe] as a function of the ICM Type Ia SNe-originating fraction of Fe. The Salpeter (1955) IMF ($x = 1.35$) was assumed, with lower and upper mass limits to Type II SNe production of 10 and 50 $M_\odot$, respectively. The horizontal dotted curve represents the mean of Mushotzky *et al.*'s (1996) ASCA SIS abundance data, as scaled to the meteoritic iron abundance by Ishimaru & Arimoto (1997). The remaining seven curves represent the theoretical predictions for seven different Type II SNe yield scenarios, as described in the text. The typical error associated with any individual cluster's ICM elemental abundance determination is indicated in each panel.

Finally, while many arguments still remain unresolved as far as the ICM Type Ia SNe iron fraction goes, it should be readily apparent from inspection of Table 3 that regardless of Type II yield compilation assumed, $\sim 90 \rightarrow 100\%$ of the ICM oxygen, silicon, magnesium, and neon originated from Type II SNe. Moreover, since Type Ia and Type II SN kinetic energies are similar but the average Fe yield 5-10 times higher for Type Ia, Type II SNe must dominate the energetics of early galactic winds – even if half of the Fe originates in Type I SNe.

3 SUMMARY

Ishimaru & Arimoto (1997) recently put the four Mushotzky et al. (1996) ASCA ICM determinations onto the meteoritic abundance scale and concluded that $\gtrsim 50\%$ of the ICM iron must have originated from Type Ia SNe. This fractional value is linked inexorably to the adopted Type II SNe yields used in their analysis – i.e. those of Tsujimoto et al. (1995).

We have re-examined the Ishimaru & Arimoto results, adopting a range of the Type II SNe models available in

Table 3. ICM Element Fraction of Type Ia Origin - For each entry of the form a/b, a represents the mass fraction of ICM O, Si, Mg, Ne, or S, that originates in Type Ia SNe, for the Type II yield source under consideration; b represents the corresponding Type Ia-originating ICM Fe fraction. The a/b pairs shown recover the mean ICM ratios illustrated in Figure 1.

Yield Source	O/Fe	Si/Fe	Mg/Fe	Ne/Fe	S/Fe
A96	0.00/0.08	n/a	0.01/0.46	0.00/0.00†	n/a
T95	0.01/0.48	0.11/0.38	0.02/0.58	0.00/0.00	0.58/0.80
T95+M92	0.00/0.00	n/a	n/a	n/a	n/a
W95;A;10^{-4}Z$_{\odot}$	0.01/0.31	0.15/0.55	0.01/0.17	0.00/0.00†	0.69/0.94
W95;B;10^{-4}Z$_{\odot}$	0.01/0.55	0.15/0.53	0.01/0.47	0.00/0.24	0.67/0.93
W95;A;Z$_{\odot}$	0.01/0.29	0.11/0.38	0.01/0.28	0.00/0.00†	0.65/0.89
W95;B;Z$_{\odot}$	0.01/0.35	0.09/0.32	0.01/0.38	0.00/0.00	0.63/0.87

†*No* mixture of Type Ia and II SNe can recover the observed ICM ratios, for the yield source in question.

the literature. These models sample a wide variety of input physics (e.g., pre-SN stellar winds, convective overshooting, reaction rates) and provide, for the first time, a better appreciation for the dependence of Type Ia versus Type II arguments on the adopted yields. Specifically, we have demonstrated that the most recent treatments of convection (Arnet 1996) and mass-loss (Maeder 1992 and Langer & Henkel 1995) *both reduce the ICM Type Ia iron fractional contribution from* $\gtrsim 50\%$ *to* $\lesssim 5\%$. This is a preliminary result that needs confirmation once full grids of Type II SNe yields are published that include self-consistent treatments of mass-loss, explosive nucleosynthesis, fall-back onto the remnant, and large atomic networks.

Several further caveats should be expressed – (i) there is no *a priori* reason why the Type II progenitors need follow an $x = 1.35$ IMF power-law slope; as noted earlier, if the slope more closely resembles a Scalo (1986) IMF ($x \approx 1.7$), then the ICM Type Ia iron fraction is reduced a further $\sim 40\%$. (ii) We have not been concerned with cluster-to-cluster differences in the effective Type Ia versus Type II contributions, only the unweighted mean. (iii) There are still fairly large statistical uncertainties in the abundance determinations (e.g., uncertainties of $\sim 25\%$, $\sim 50\%$, $\sim 50\%$, $\sim 100\%$, and $\sim 100\%$, for Si/Fe, O/Fe, Ne/Fe, Mg/Fe, and S/Fe, respectively). (iv) All Type Ia yields are tied exclusively to the W7 model of Thielemann et al. (1993). (v) The $10 \rightarrow 13$ M$_{\odot}$ yields are essentially unknown; we have extrapolated from the lower-mass limits in the various grids, but there is no reason to suspect that this is entirely satisfactory. For the IMFs discussed in this paper, $\sim 20 \rightarrow 25\%$ of the mass in a stellar generation is locked up in this uncertain regime.

In conclusion, while our model predictions for the ICM [O/Fe] appear to favour a highly dominant Type II SNe origin to the ICM iron, especially when coupled with the Maeder (1992), or Arnett (1996) oxygen yields, we cannot unequivocally state that this is the case – there still exists much uncertainty in the massive star models (in particular, convection mass-loss, reaction rates, location of the iron "cut", and fall-back onto the remnant). Regardless of the lack of a definitive answer as to the Type Ia versus Type II ICM iron origin, this study does illustrate its underappreciated sensitivity to the adopted Type II SNe yields.

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REFERENCES

Anders, E. & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Arnett, D. 1991, Frontiers of Stellar Evolution, ed. D.L. Lambert, ASP Conf. Series, 389
Arnett, D. 1996, Supernovae and Nucleosynthesis, Princeton: Princeton Univ. Press
Bazán, G & Arnett, D. 1997, ApJ, submitted
Canizares, C.R., Clark, G.W., Jernigan, J.G. & Markert, T.H. 1982, ApJ, 262, 33
Canizares, C.R., Markert, T.H. & Donahue, M.E. 1988, Cooling Flows in Clusters and Galaxies, ed. A.C. Fabian, Dordrecht: Kluwer, 63
Caughlan, G.R., Fowler, W.A., Harris, M.J. & Zimmerman, B.A. 1985, At. Data Nucl. Data Tables, 32, 197
Gibson, B.K. 1997, MNRAS, in press
Gibson, B.K. & Matteucci, F. 1997, ApJ, 475, 47
Ishimaru, Y. & Arimoto, N. 1997, PASJ, 49, 1
Langer, N. 1997, The History of the Milky Way and its Satellite System, ASP Conf. Series, in press
Langer, N. & Henkel, C. 1995, Space Sci. Rev., 74, 343
Loewenstein, M. & Mushotzky, R.F. 1996, ApJ, 466, 695
Maeder, A. 1992, A&A, 264, 105 (Erratum: 1993, A&A, 268, 833)
Matteucci, F. & Vettolani, G. 1988, A&A, 202, 21
Mushotzky, R., Loewenstein, M., Arnaud, K.A., Tamura, T., Fukazawa, Y., Matsushita, K., Kikuchi, K. & Hatsukade, I. 1996, ApJ, 466, 686
Rothenflug, R.L., Vigroux, R., Mushotzky, R. & Holt, S. 1984, ApJ, 279, 53
Salpeter, E.E. 1955, ApJ, 121, 161
Scalo, J.M. 1986, Fund. Cosmic Phys., 11, 1
Thielemann, F.-K., Nomoto, K. & Hashimoto, M. 1993, Origin and Evolution of the Elements, ed. N. Prantzos, E. Vangioni-Flam, & M. Cassé, Cambridge: Cambridge Univ. Press, 297
Thielemann, F.-K., Nomoto, K. & Hashimoto, M. 1996, ApJ, 460, 408
Tsujimoto, T., Nomoto, K., Yoshii, Y., Hashimoto, M., Yanagida, S. & Thielemann, F.-K. 1995, MNRAS, 277, 945
Woosley, S.E. & Weaver, T.A. 1995, ApJS, 101, 181